Traveler I: Sub-Orbital Flight Demonstration of MEMS Technologies

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Student Microsatellite Program

University of Southern California

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Introduction

- Micro-Technology (MEMS) Demonstration
  - MEMS Technologies Could Benefit From Frequent Access to Space
    - Proof-of-Principle demonstration
    - Testing of incremental changes
    - Lifetime testing
    - Rapid Identification of enabling technology
  - Benefits From University Technology Demonstration
    - Simple experiments can be performed
    - Quick turn around (conception to integration)
    - Additional resources available

Research-Based Microsatellite Program

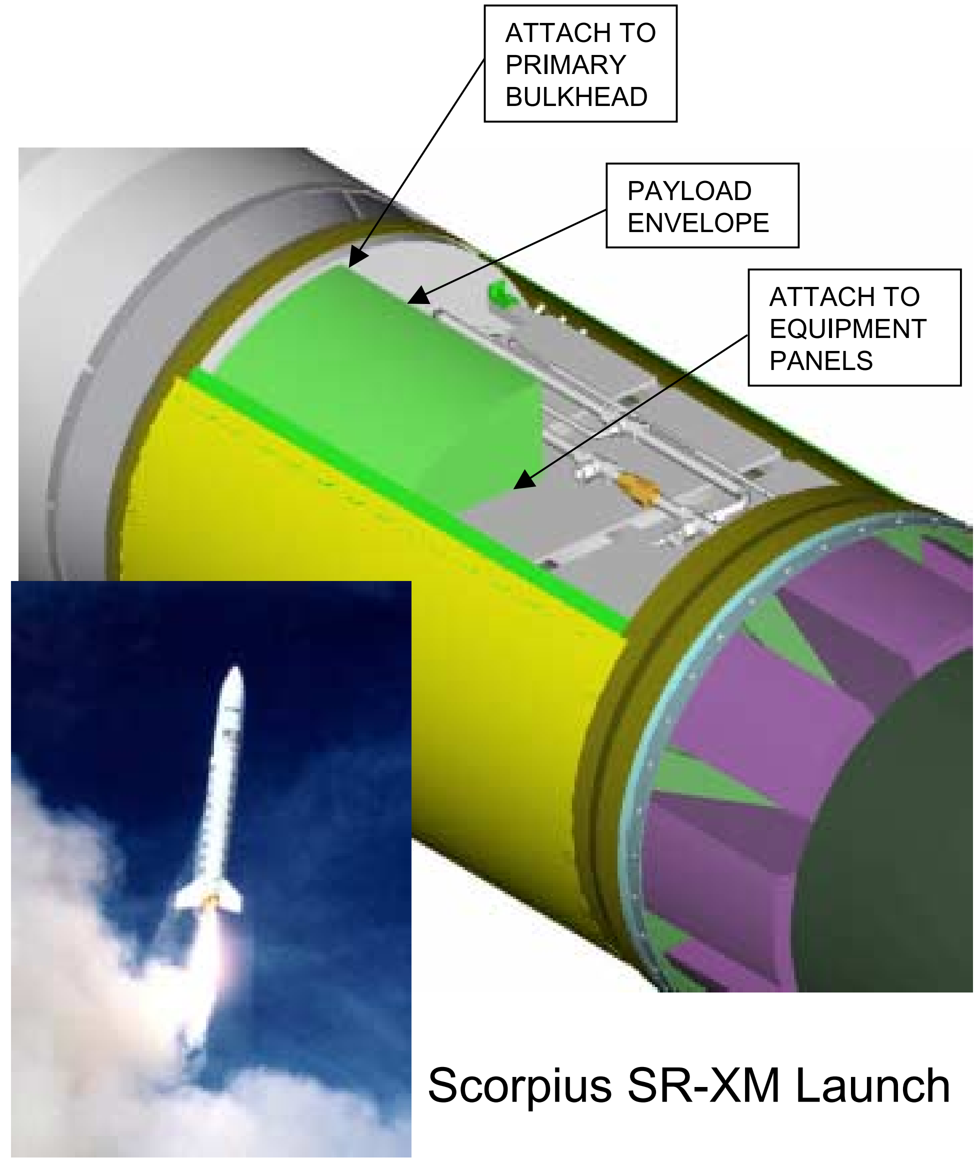
- Leveraging of Faculty/Industry/Government Funded Research Is Driven By
  - Willingness to find synergies
  - Reasons to find synergies
- Allows a Program Philosophy Unique Among US Universities
  - Missions are more difficult and risky
    - State of the art technologies
    - Minimal testing on the ground
  - More difficult missions bring excitement

USC Microsatellite Program – Brief Overview

- 140 Dedicated Students
  - 120 Undergraduate students
  - 20 Graduate students (6 Ph.D. students)
- Mentor program
  - Faculty
  - Industry
  - Government
  - Students
- Program Philosophy
  - Crawl: Shopping Cart Sat
  - Walk: Balloon Sat
  - Run: Traveler I
  - Fly: Aeneas (MEMS Tech. Demo.)

Traveler I: Launch

- Launch Vehicle
  - Scorpius SR-XM-2
  - Sub-Orbital Launch
  - Mid-2003 Launch Date
- Flight Parameters
  - Engine Burn: 127 sec (20,000 lb. thrust engine)
  - Flight Duration: 630 sec
  - Maximum Altitude: 330 km
  - Maximum Acceleration ~ 10 G's
  - Benign Vibration Levels Anticipated



Scorpius SR-XM Launch

Traveler I: Experiments

Experiment Equipment Box
Characterization
COTS Components
(Accelerometers, Pressure, Temperature)
(2 kg, 0.5 W)

3-Axis Magnetometer
(4 kg, 3 W)

Micro-Propulsion Experiment
(MEMS)
FMMR

Micro-Pump Experiment
(MEMS)
Knudsen Compressor

Micro-Propulsion Experiment
FMMR Propellant Tank

3 kg,
3.5 W

Traveler I: Knudsen Compressor

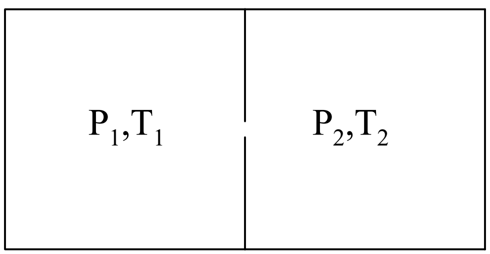
- Addresses need for micro-scale vacuum pump for spacecraft sensors (e.g. mass spectrometers)
- No moving parts.
- No oil or working fluids.
- Recent availability of small pore membrane materials with very low thermal conductivities.
- Can operate on waste heat from other equipment.
- MEMS fabrication allows for batch fabrication of the many required stages.
- Can operate over a wide range of pressures.
  - Roughing pump from 10 mTorr – 1 atm
  - High pressure compressor from 1 atm to 10 atm

Traveler I: Knudsen Compressor

Rarefied gas phenomena (free-molecular flow driven by gas-surface interactions)

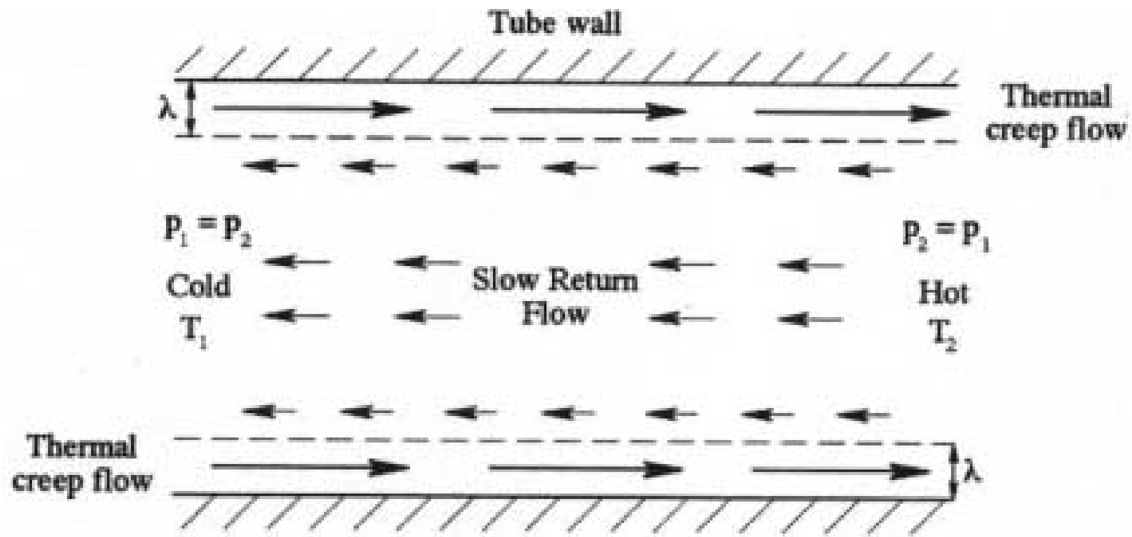
Thermal Effusion Through Orifice

$T_1 < T_2$



$$\frac{p_1}{p_2} = \sqrt{\frac{T_1}{T_2}}$$

Thermal Creep along surfaces



- Longitudinal Wall temperature gradient drives creep flow, counterbalanced by pressure driven return flow (Poiseuille flow)
- One of the driving mechanisms in Crooke's radiometer

Net effect is a flow from cold to hot side of tube

Traveler I: Knudsen Compressor

$$TMPD = \frac{\nabla P / P}{\nabla T / T}$$

Flow in a Knudsen Compressor is the difference between thermal creep and pressure driven return flows

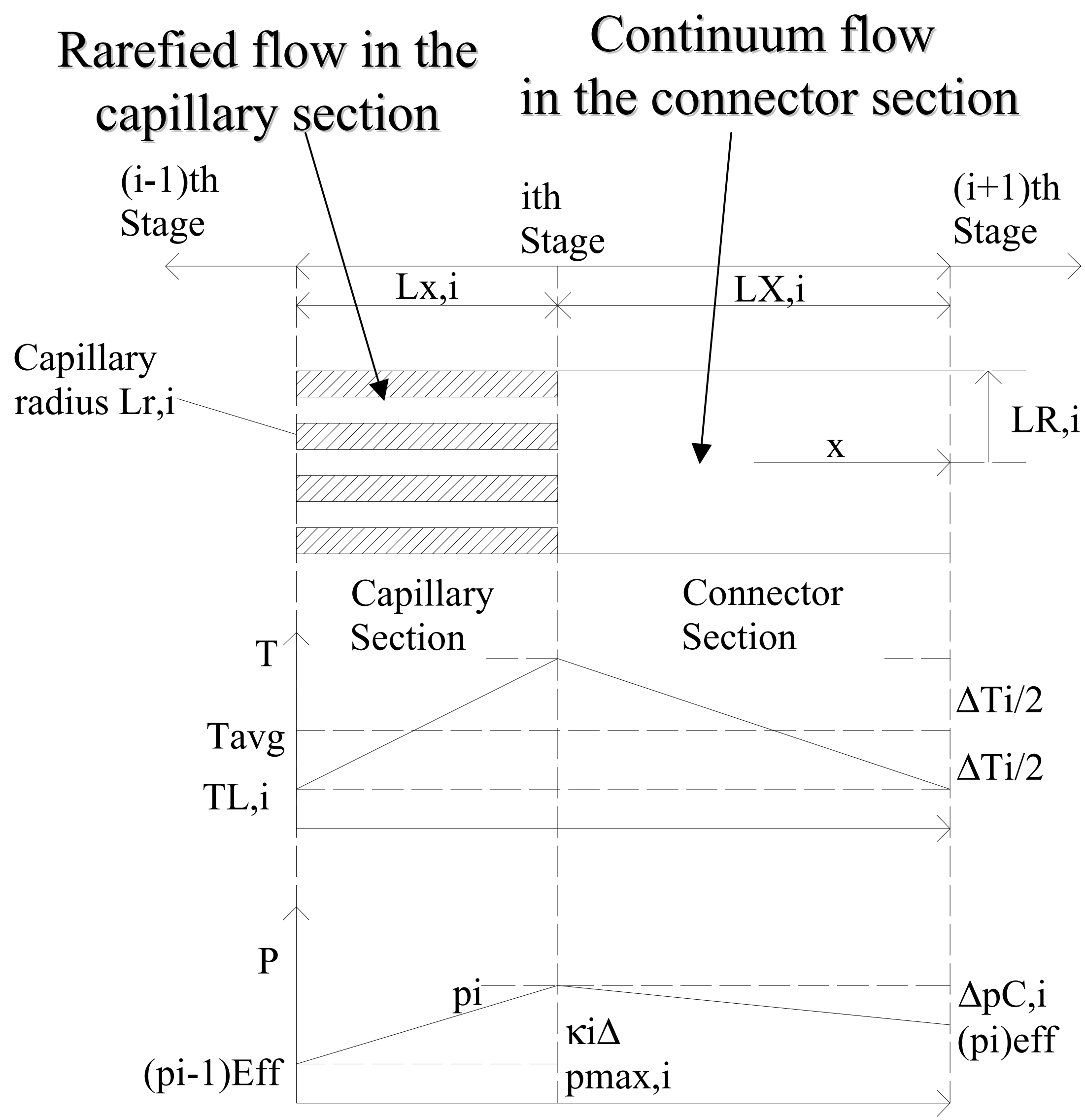
<u>FM equations</u>

$$\dot{N}_T = \left\{ \frac{\sqrt{\pi}}{12} n_v v_o d^3 \right\} \frac{\nabla T}{T}$$

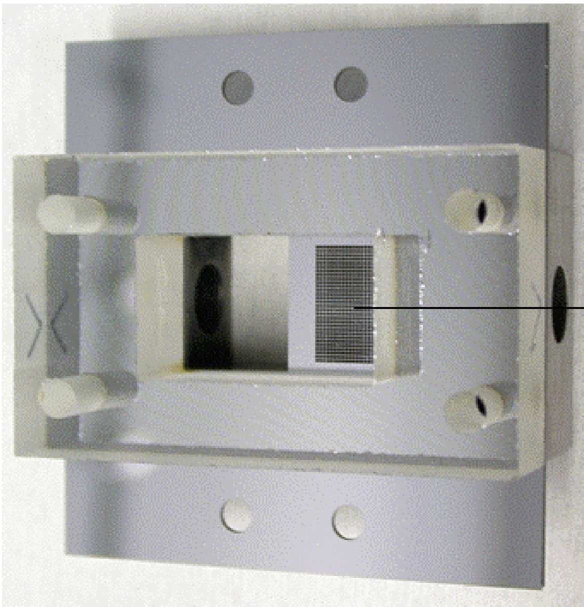
$$\dot{N}_p = \left\{ -\frac{\sqrt{\pi}}{6} n_v v_o d^3 \right\} \frac{\nabla p}{p}$$

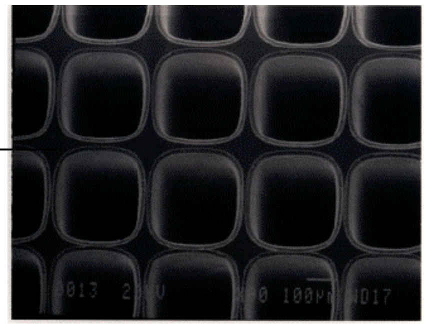
$$\mathrm{TMPD}_{\mathrm{FM}} = ½$$

$$\mathrm{TMPD}_{\mathrm{Cont}} = 0$$

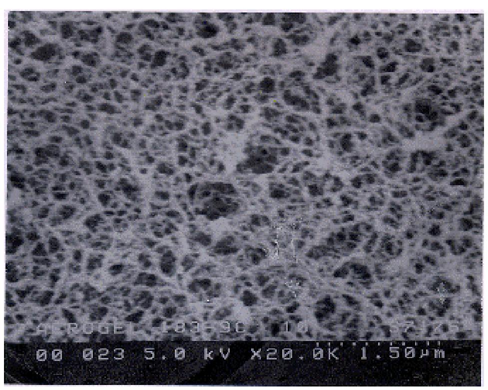


Traveler I: Knudsen Compressor

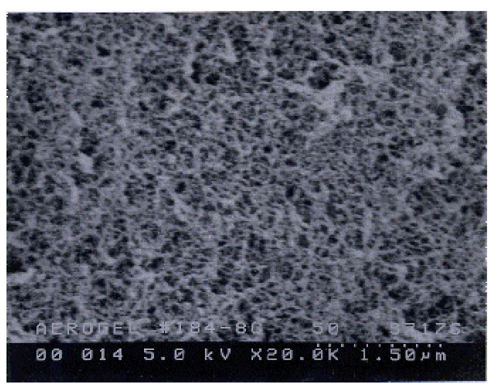




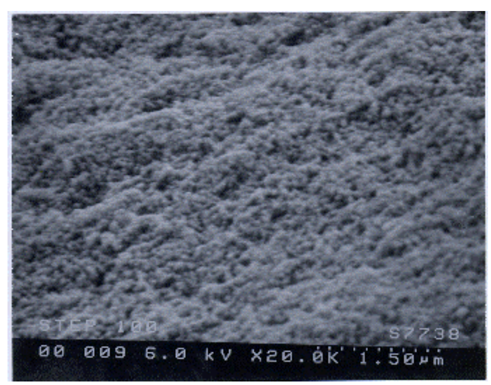
- Membrane is made from Si aerogel
- 0.6mm thick x 8mm x 10mm
- Optically heated to provide pumping



ρ = 10mg/cc

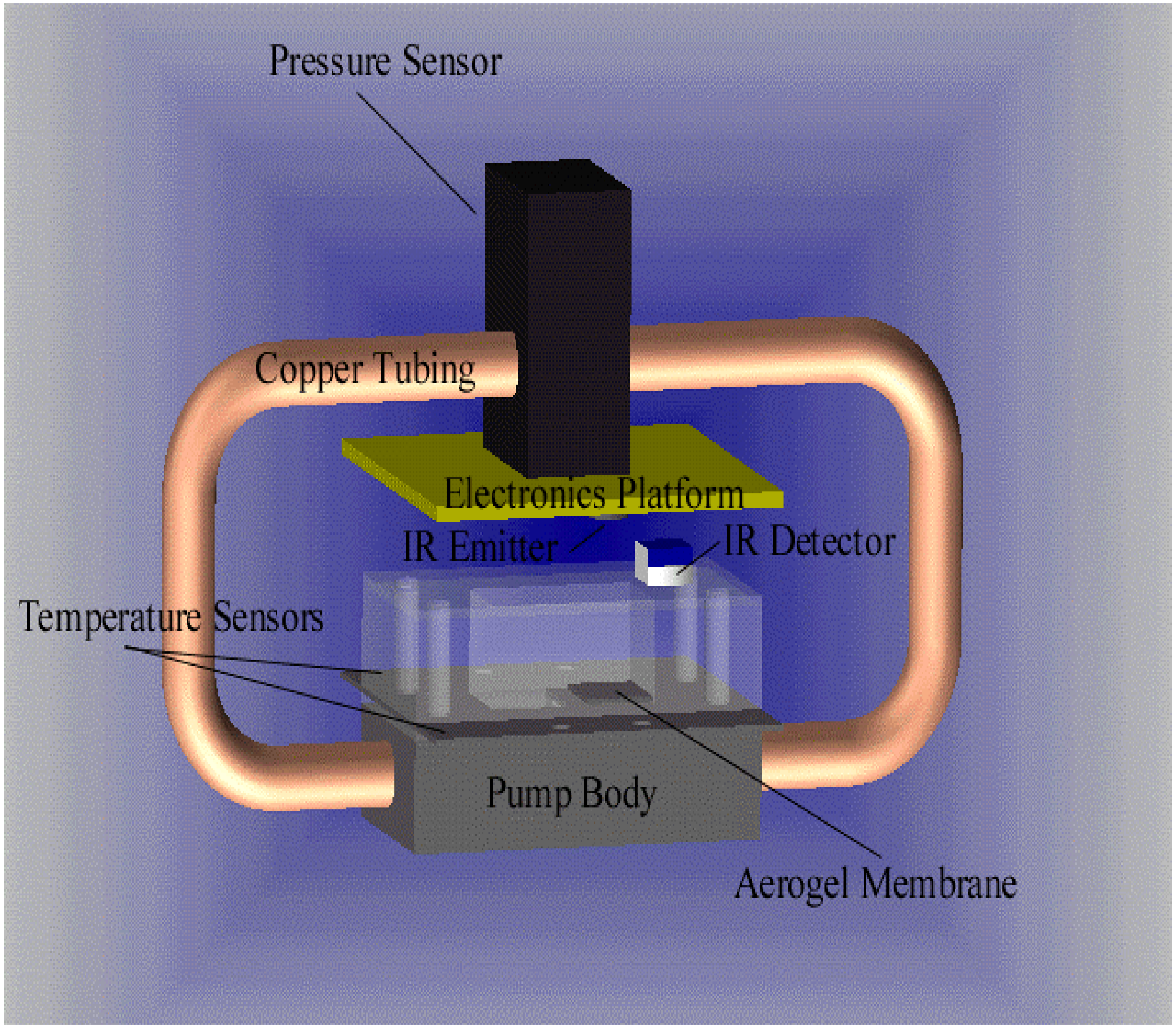


ρ = 50mg/cc



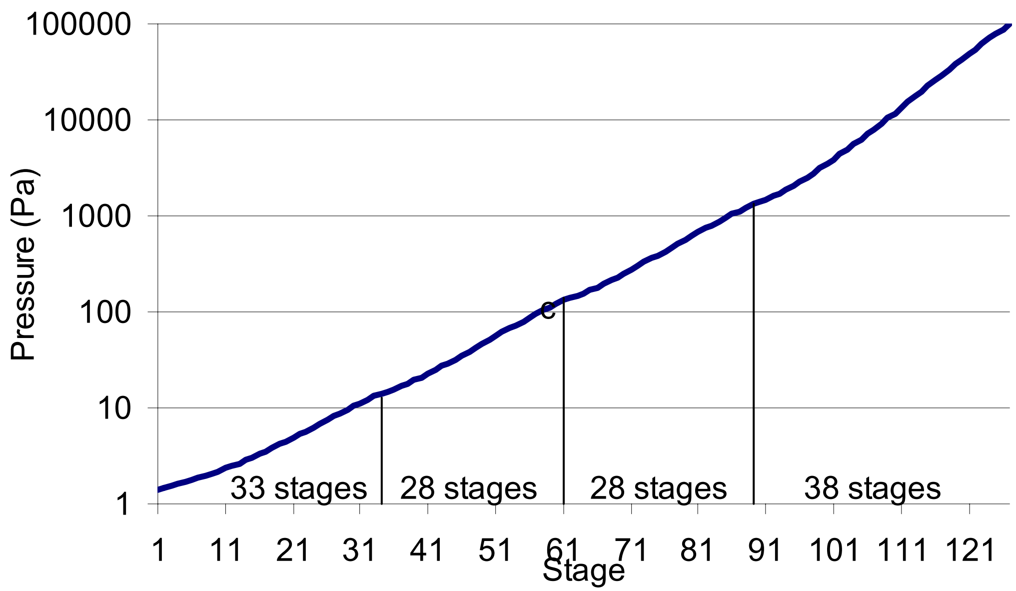
ρ = 100mg/cc

Traveler I: Knudsen Compressor



Traveler I: Knudsen Compressor

Cascade	Volume (cm^3)	Power (W)
10-100 mTorr	45.1	1.07
100mTorr-1Torr	13.0	0.297
1Torr-10Torr	11.8	0.268
10Torr-760Torr	5.26	0.92
Total	75.2	2.56



Power Efficiency	8.5E-17 W/(#/s)
Volumetric Efficiency	2.5E-21 m^3/(#/s)

Traveler I: Knudsen Compressor

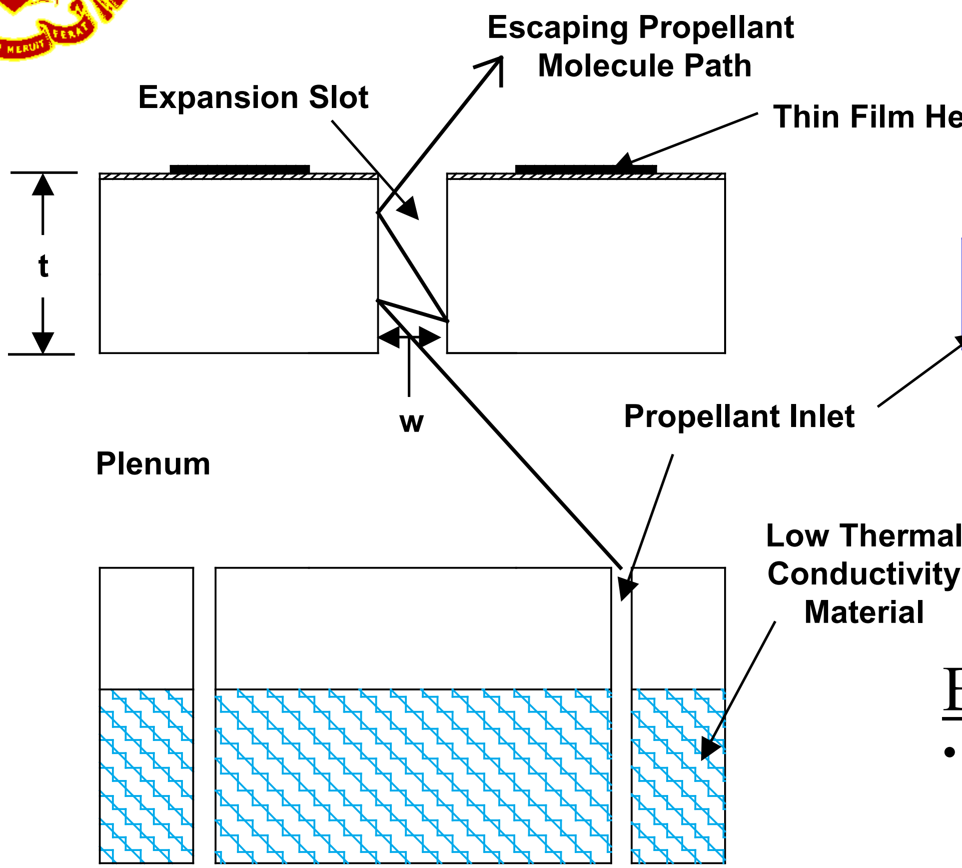
- Pump system will be evacuated and then filled with slightly less than 1 atm of N_2
  - Single specie easier to analyze
  - Lower pressure allows leaks to be determined
- Flight Profile:
  - Pump illuminated
  - pressure difference vs. time measured
  - maximum pressure measured

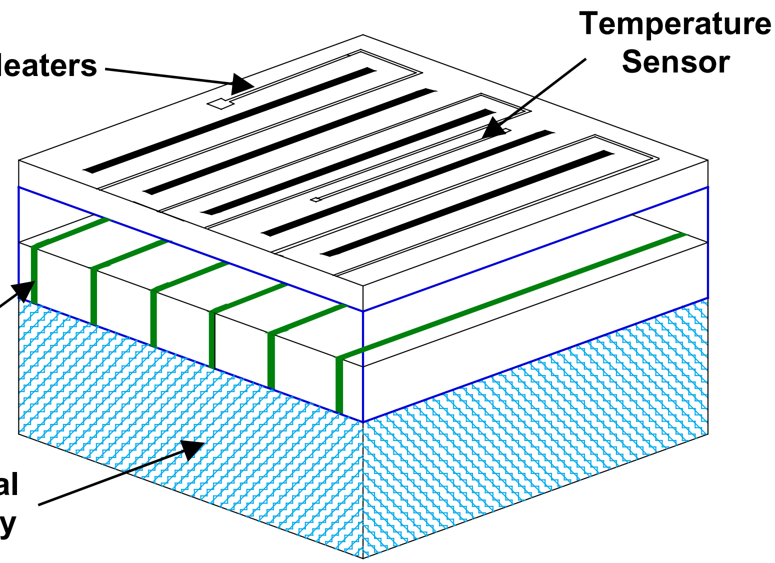
For More Information, Contact: Marcus Young – marcusyo@spock.usc.edu

Traveler I: Free Molecule Micro-Resistojet (FMMR)

- On-orbit maneuvering of nanospacecraft (m <= 10 kg)
  - Mission enabling
  - Altitude raising, attitude control, drag makeup, stationkeeping
- Micro-thruster efficiency is extremely important
  - Extremely mass, volume and power limited
  - Rule of thumb: 1 W/kg power available
  - 10 kg spacecraft $\Rightarrow$ 3-7 W available for propulsion
- Free Molecule Micro-Resistojet (FMMR)
  - MEMS fabricated electrothermal propulsion system
    - Low stagnation pressure operation (50-500 Pa)
    - Small characteristic dimensions, batch fabrication
    - Electrically heat propellant flow on

Traveler I: FMMR





Benefits

- Low pressure operation
  - Reduces MEMS valve leakage
  - Reduces propellant storage tank mass
- Phase change of propellant
  - Operates on propellant vapor pressure
  - Reduces storage volume
- Reduces likelihood of single point failures
- Permits large range of thrust levels without significant loss in performance

Concept

- Systems approach has driven creative basis for the FMMR
- Example of how fluid/gas dynamics at micron scales can be beneficially exploited

Traveler I: FMMR

- Uniform Free Molecule Flow Through a Finite L/D Slot

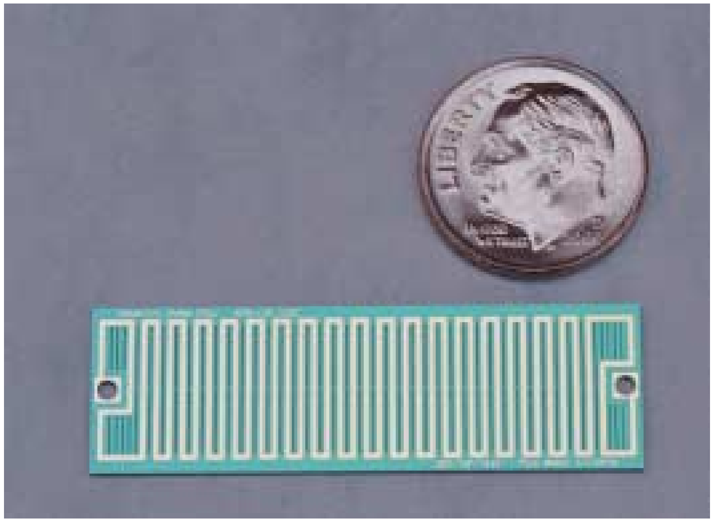
$$\Im = \alpha \frac{d(mu)}{dt} A_s$$

$$\Im = \alpha \frac{n_p k}{2} \sqrt{T_i T_w} A_s$$

$$\dot{m} = \alpha m \frac{n_p \bar{c}'}{4} A_s = \alpha \frac{m n_p}{4} \sqrt{\frac{8kT_i}{\pi m}} A_s$$

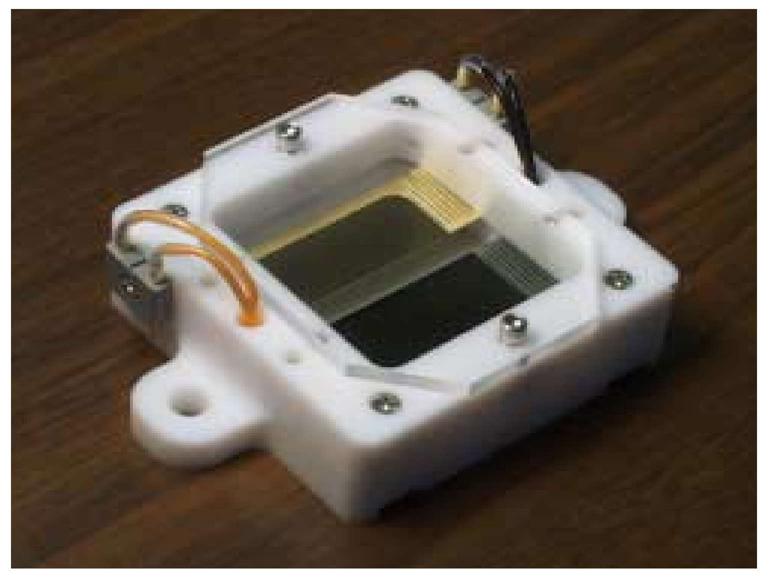
$$I_{sp} = \frac{\sqrt{\frac{\pi k T_w}{2m}}}{g_o}$$

Traveler I: FMMR



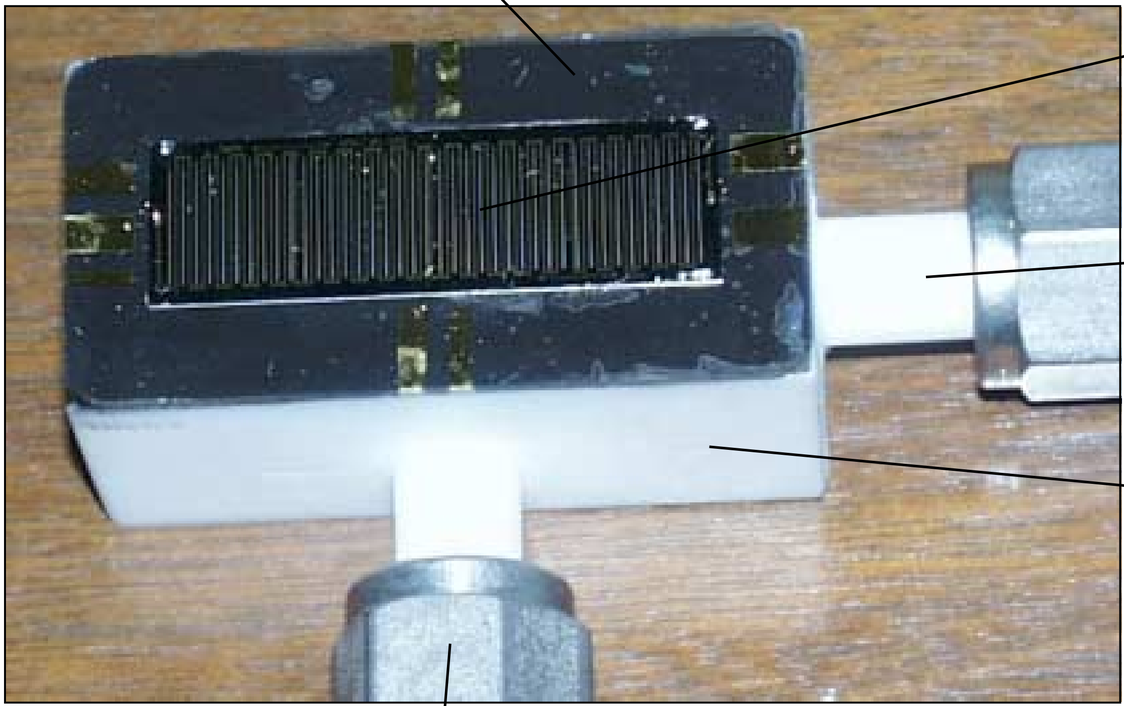
- FMMR Scheduled for Flight on ASU/UNM/CU 3-Corner Sat Mission
- Traveler I will test MEMS Packaged FMMR (3CS Macro-packaged)
- Shuttle Flight of 3CS Mission Will Be Complimented by 10 G Scorpius Launch

- 13 x 42mm, 400µm-thick LSN wafer
- Heater
  – Cr (300Å) + Pt (600Å) + Au (8000Å)
  – 400µm wide, 0.45m total length
- Expansion slots
  – 50 slots
  – 100µm wide, 3 to 5mm long



Traveler I: FMMR

- FMMR Packaging



Traveler I: FMMR

- Important for fluid flow management in MEMS devices
- Bond strength important for the design of MEMS components
- Bond strength determines:
    - Maximum pressure handling capability
    - Minimum bond width required for a given pressure
- The voltage and temperature used during the bonding affect the pulling strength.
- Separate Anodic Bond Experiment tests:
    – Materials
    – Thickness
    – Voltage
    – Temperature
- FMMR and Knudsen Compressor also incorporate anodic bonding

Traveler I: FMMR

- Bonding requires a conductive substrate and a sodium-rich glass substrate
- A voltage potential is applied across the substrates
- Positive ions migrate towards the cathode
- Electrostatic attraction holds materials together

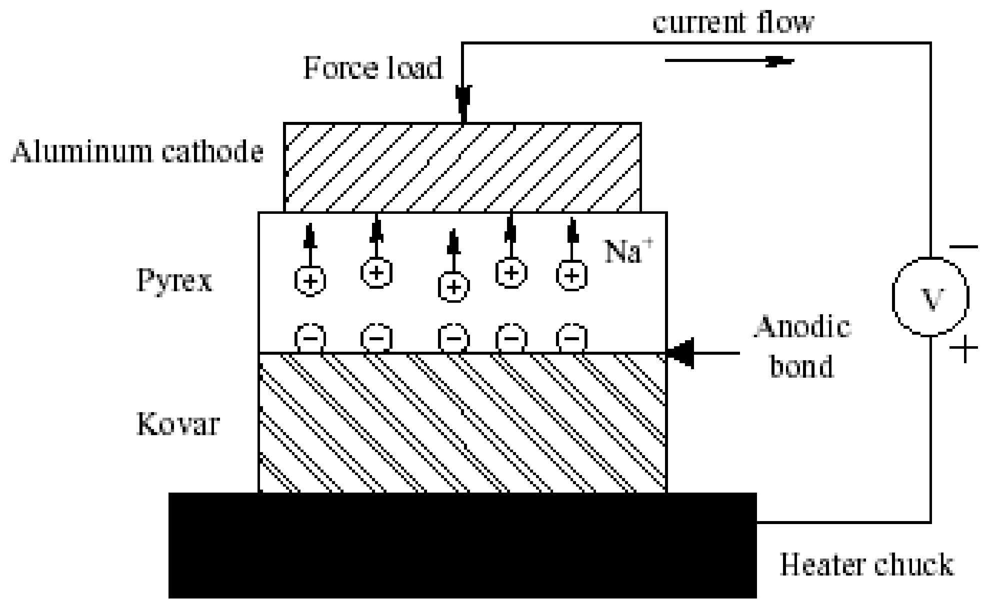


Figure 1. Schematic of the anodic bonding apparatus.[3]

Maluf, N

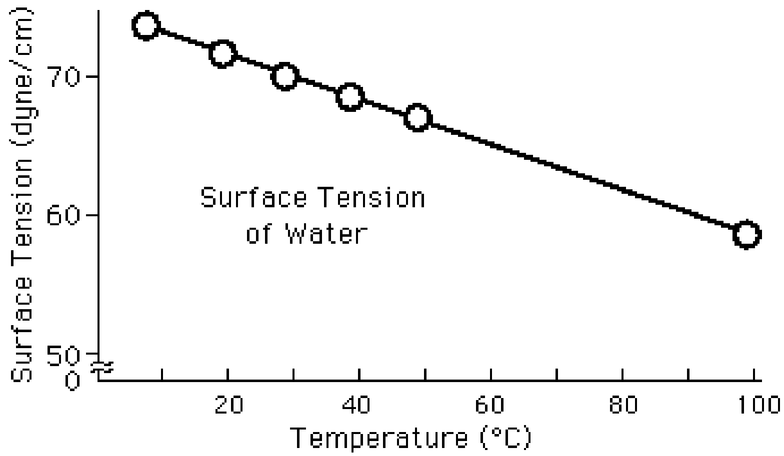
Traveler I: FMMR

Material 1	Thickness	Material 2	Thickness	Voltage	Temp(C)
Silicon	400 μm	Pyrex	0.5 mm		
Silicon	400 μm	Pyrex	6.25 mm		
Kovar	1.0 cm	Pyrex	0.5 mm	1200	380
Kovar	1.0 cm	Pyrex	9 mm	1200	380
Kovar	1.0 cm	Pyrex	1.5 mm	1200	380
Kovar	1.0 cm	Pyrex	1.5 mm	1800	225
Kovar	1.0 cm	Pyrex	1.5 mm	1900	211
FMMR Silicon	400 μm	Pyrex	1.0 mm		
Knudsen					

Traveler I: FMMR Propellant Tank

- Water used as a propellant for the FMMR due to its favorable vapor pressure at typical microsatellite temperatures
- Isolate water in propellant tank away from valves, regulators, and nozzle (mitigate freezing issues)
- Use surface tension of liquid to passively manage propellant
  - No power required to heat assembly
  - Will not allow liquid water to pass (hydrophobic)
  - Sufficient open area to allow water vapor to pass (FMMR propellant)

Traveler I: FMMR Propellant Tank

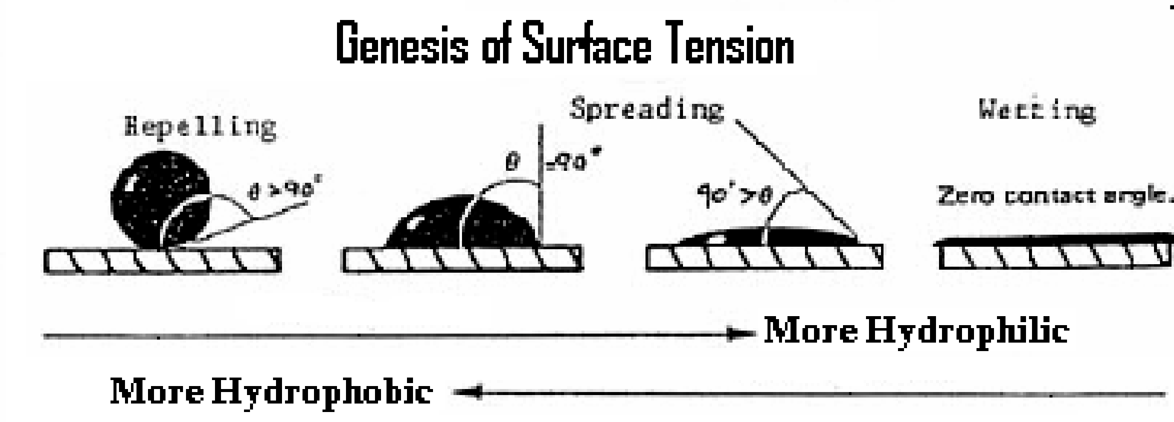


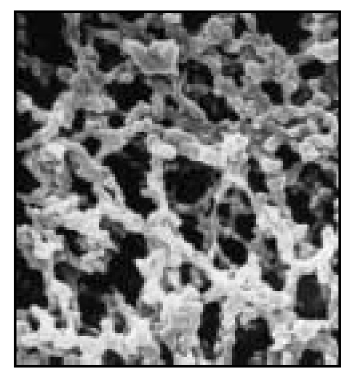
$$F_{st} = \gamma(T)\cdot 2\pi r\cdot\cos(\theta)$$

$$F_w = \rho\cdot N\cdot g\cdot h\cdot\pi(r)^2$$

Want to counteract F_w with liquid propellant surface tension

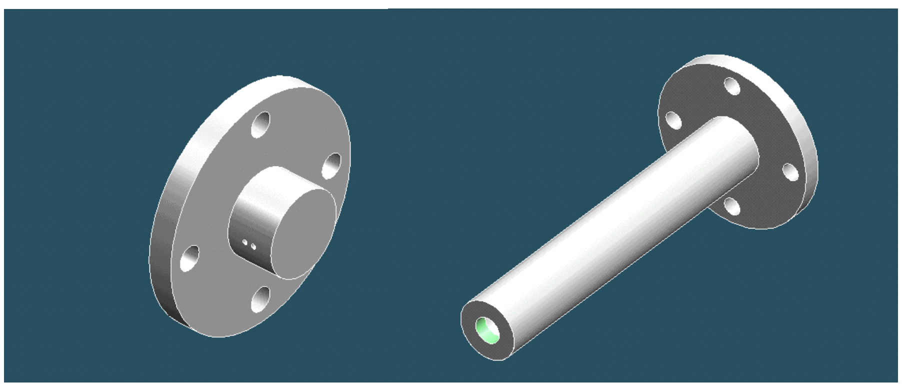
Nano-porous material needed with average pour diameter less than 700 nm in non-wetting material

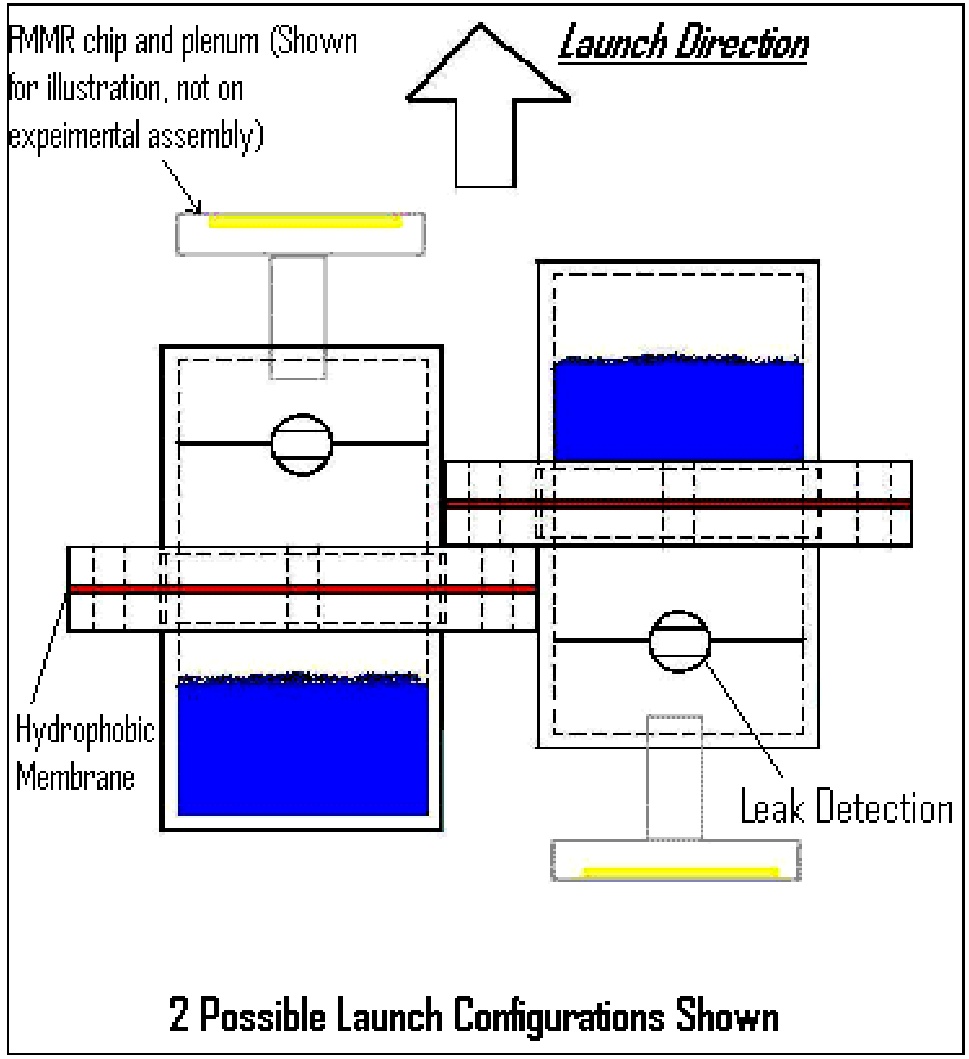




Traveler I: FMMR Propellant Tank

- Two Propellant Tanks
- Multiple orientations
  - Worst case scenario
  - Best case scenario
- Water detection circuit





Traveler I: PDR

- Preliminary Design Review
  - 20 April 2002
  - 9 AM to 5:30 PM (USC Campus)
  - Web Simulcast
  - Web-cast will be archived on website
- More Information
  - Call: 213-740-1635
  - http://microsat.usc.edu
  - e-mail: aesat@spock.usc.edu
  - Newsletter (copies available)

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